# Structure of an Evolving Hailstorm, Part IV: Internal Structure from Penetrating Aircraft

D. J. MUSIL, E. L. MAY,[1] P. L. SMITH, JR., AND W. R. SAND

*Institute of Atmospheric Sciences,*[2] *South Dakota School of Mines and Technology, Rapid City, S. Dak. 57701*

(Manuscript received 17 September 1975, in revised form 24 December 1975)

ABSTRACT

Precipitation particle sizes were measured using a continuous hydrometeor sampler (foil impactor) during penetrations of hailstorms with an armored T-28 aircraft. Data have been analyzed from three penetrations of a storm near Raymer, Colorado, on 9 July 1973 at altitudes between 5.5 and 7.2 km MSL, which correspond to temperatures between about −2°C and −12°C. Other results pertinent to the Raymer storm are discussed in Parts I, II, III and V elsewhere in this issue.

Most of the particles were identified as ice particles or ones containing both ice and water; however, significant amounts of liquid particles were found in the updrafts of developing cells at temperatures as cold as −12°C. Particles larger than 5 mm in diameter were typically found along the edges of the updrafts, with the precipitation concentrations being strongly dependent on these larger particles. The downdrafts were composed of ice particles.

Several particle size distributions from one of the penetrations were examined. The distributions are roughly exponential, or bi-exponential when large particles are present.

## 1. Introduction

There have been numerous investigations of particle size distributions from precipitation observations made at the ground using camera devices and impact devices (e.g., Cataneo and Stout, 1968; Waldvogel, 1974; Federer and Waldvogel, 1975). Investigations of in-cloud particle sizes have used airborne foil impactors based on a principle first described by Brown (1958) but have necessarily been restricted to small cumuli (Bethwaite *et al.*, 1966; Schroeder, 1973) and frontal clouds (Cornford, 1966). Systematic observations within hailstorms and thunderstorms are virtually nonexistent because of the difficulty and danger involved in obtaining them.

During the 1973 National Hail Research Experiment (NHRE) field season, a continuous hydrometeor sampler (foil impactor) was flown aboard an armored T-28 aircraft and obtained observations of particle sizes on a routine basis. The purpose of this paper is to present the results of a detailed analysis of the foil data obtained from penetrations of a hailstorm occurring near Raymer, Colo., on 9 July 1973. This paper can be viewed as an extension of the work by May (1974), who initially analyzed the foil data. The paper is part of a comprehensive analysis of data from the Raymer storm by several participants in NHRE which appears elsewhere in this issue (see Parts I, II, III and V).

[1] Current affiliation: National Weather Service, Detroit, Mich.

[2] This research was performed as part of the National Hail Research Experiment managed by the National Center for Atmospheric Research and sponsored by the Weather Modification Program, Research Applications Directorate, National Science Foundation, Grant C-460 and Subcontract NCAR 182-71.

## 2. Data collection and reduction

The foil impactor was flown aboard an armored T-28 aircraft operated by the South Dakota School of Mines and Technology. The mode of operation and other information collected by the T-28 system have been described by Sand and Schleusener (1974).

Typically the T-28 mission consisted of gathering data during penetrations of active hailstorms beginning at an altitude[3] of about 7.3 km and proceeding downward by 0.6 km intervals until 4.9 km was reached. The aircraft was vectored with the objective of entering the maximum radar reflectivity zone and major updraft at aircraft altitude on each storm penetration. A penetration was usually made at a constant heading until clear air was encountered or until the T-28 was well clear of any radar echoes. Typically, three to six penetrations were made on each mission.

### a. Description of foil impactor

The foil impactor has a moving strip of soft aluminum foil approximately 7.5 cm wide and 30 $\mu$m thick, which passes by an open window with dimensions of 3.75 cm by 3.75 cm at a speed of about 3.8 cm $s^{-1}$. The foil is backed by a ridged drum so that when ambient air

[3] All heights are given with respect to mean sea level.

strikes the foil, particles in the air leave impressions on the foil. The particle sizes can be determined from marks left within the imprints on the foil by the ridges on the drum, which are spaced at 250 μm increments. Thus the smallest particles and the diameter resolution of particles included in this study are of the order of 0.25 mm.[4]

The foil impactor face plate is electrically heated to minimize icing problems that can occur in the severe environments of the storm penetrations. The supply roll of foil is large enough for approximately thirty minutes of in-cloud observations, which is sufficient for most missions.

### *b. Data reduction*

Data reduction is extremely time consuming, so initially the analysis was limited to penetrations made on two days in which the greatest vertical air motions were observed and the pilot's comments indicated the analysis of the foil would be most productive. Only the analysis of data from the Raymer storm will be presented in this paper.

The foil was marked off into sections (or frames) each representing four seconds of observation time, which corresponds to a flight path of about 0.4 km and a sampling volume of about 0.6 m³. The particle numbers and sizes were recorded for each frame.

Particles that could be distinguished as completely liquid were recorded separately from those that were completely solid or contained some fraction of ice. The identification of liquid particles is quite simple (Miller *et al.*, 1967) because they leave circular imprints with raised edges. Particles that are composed partly or wholly of ice tend to leave irregular, splattered imprints, making it impossible to determine the amount of liquid in such a particle. The "combination" particles were recorded as ice in this study.

Imprint sizes less than 7.5 mm were corrected according to an expression developed from work by Schecter and Russ (1970). The correction is for an approximate true airspeed of 100 m s$^{-1}$ and is necessary to account for the distortion of the particles upon impact on the foil. Beyond 7.5 mm, where no calibration data exist, the particle sizes were taken to be the same as the imprint sizes. The imprint sizes are probably larger than the actual sizes for all particles encountered, as is indicated by the Schecter and Russ work for particles smaller than 7.5 mm; however, extrapolation of their correction procedure would lead to the opposite result for large sizes and in extreme cases would even require particles too large to enter the window of the foil impactor.

In order to obtain samples large enough to reduce some of the errors associated with small sampling volumes (Joss and Waldvogel, 1969), data from three consecutive frames were summed to form a sample for which we computed the total number concentration for all particles observed on the foil ($N_t$), the concentration of particles larger than 5 mm ($N_5$), the precipitation concentration for particles larger than 0.25 mm (PC), and the percent mass liquid (PML). Then the last frame of the set was retained and added to the next two consecutive frames and the calculations repeated. In this manner, smoothed data points were obtained for each 8 s representing a 12 s running average that corresponds to a flight path of about 1.2 km and a sample volume of about 1.8 m³.

[4] All particle sizes are expressed in diameters.

TABLE 1. Summary of penetration data for 9 July 1973.

| PENETRATION | | 80—1 | 80—2 | 80—3 |
|---|---|---|---|---|
| DATE | | 9 JULY 1973 | | |
| START TIME | | 171636 | 172904 | 174147 |
| END TIME | | 172322 | 173649 | 175112 |
| AVG ALT-(km) | | 7.2 | 5.9 | 5.5 |
| AVG TEMP-(°C) | | -12 | -5 | -2 |
| VOL SAMPLED-(m³) | | 59.2 | 68.0 | 81.9 |
| $N_t$ (m$^{-3}$) | % | 100 | 97 | 100 |
| | MAX | 268 | 440 | 352 |
| | AVG | 92 | 119 | 101 |
| | σ | 65 | 111 | 96 |
| $N_5$ (m$^{-3}$) | % | 42 | 20 | 25 |
| | MAX | 7.2 | 11.6 | 3.0 |
| | AVG | 3.3 | 4.8 | 1.7 |
| | σ | 2.5 | 3.5 | .9 |
| PC (g m$^{-3}$) | % | 48 | 46 | 49 |
| | MAX | 2.0 | 2.1 | 1.1 |
| | AVG | 0.7 | 0.6 | 0.3 |
| | σ | 0.6 | 0.7 | 0.3 |

## 3. General observations

Pertinent data and summaries from penetrations of the Raymer storm are given in Table 1. The penetrations were made between altitudes of approximately 5.5 and 7.2 km MSL, which correspond to temperatures of about −2°C to −12°C. These temperatures are based on adiabatic ascents from observed cloud base using the appropriate radiosondes on 9 July (Part I). Temperatures actually observed during the penetrations were not used because one of the T-28 temperature probes was subject to wetting and freezing, while the second probe was subject to significant day-to-day calibration drift.

Also shown in Table 1 are the maxima, means, and standard deviations (σ) for $N_t$, $N_5$, and PC for each penetration. Not included in the averages were regions having PC values less than 0.1 g m$^{-3}$. Average values of $N_t$ and PC are lower than might be expected in view of their associated maxima because the penetrations showed the clouds to be composed of large areas where few particles were encountered. The percentages shown

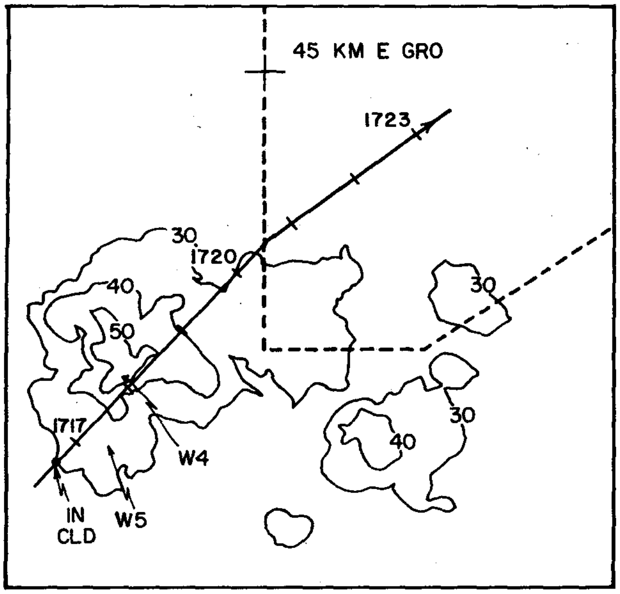


FIG. 1. Slant PPI display near time and altitude of Penetration 80-1. The radar elevation angle and time of scan are 7.0° and 171838 MDT, respectively. Reflectivity factor contours are indicated in dBz. The heavy line shows the aircraft track with the large dot denoting visual cloud entry at 171637 MDT. The tick marks along the track are at even one minute intervals. The time scale on this and succeeding figures can be converted to a distance scale by noting that aircraft speed is about 6 km min$^{-1}$.

for each variable refer to the fraction of time during the penetration that each variable was observed. Thus, it can be seen that large particles ($N_5$) were found in relatively small regions of the cloud compared to the total concentration ($N_t$), for which values near 100% indicate that there were almost always some particles striking the foil impactor during a penetration.

The total number concentrations are lower than those normally observed in rainfall at the ground. This is also indicated by the particle size distributions discussed in Section 4b, which generally show fewer particles but more large ones than the familiar Marshall-Palmer distribution would suggest. This may indicate that the processes of raindrop breakup and/or evaporation and shedding of water by falling hailstones modify the particle size distributions appreciably before the precipitation reaches the ground.

A close relationship exists between PC and $N_5$ (the relationship is more apparent in the plots of Fig. 3 than in the values of Table 1), indicating that the large particles contribute most of the PC. Thus, significant precipitation concentrations are also restricted to smaller regions of the cloud than $N_t$. The observed precipitation concentrations are in general agreement with those reported by Schroeder (1973) and in Texas.[5]

[5] See San Angelo Cumulus Project annual reports for FY1972 and FY1973 by Meteorology Research, Inc., Altadena, Calif. Reports prepared for Texas Water Development Board.

## 4. The Raymer storm

All three penetrations of the Raymer storm were in part of Storm W described in Part I. Figure 1 shows a contoured slant range PPI display from the Grover 10 cm radar near the time and altitude of Penetration 80-1, with the aircraft flight path superimposed.

Penetration 80-1 was made near the center of a newly developing cell (W5) and along the southeastern edge of the high reflectivity region of a more mature cell (W4). Subsequent penetrations, 80-2 and 80-3, were in Cell W5; however, information from Penetration 80-1 will be emphasized in this paper because it was the most interesting and the air space limitations on 9 July prevented traversing the desired regions on Penetrations 80-2 and 80-3. Even on Penetration 80-1, we were prevented from penetrating the most preferred regions of the cloud, which were along a more north-south or northwest-southeast line that would intercept both the high reflectivity zone and the updraft region.

The large dot shown at the beginning of the aircraft track in Fig. 1 corresponds to entry into the visual cloud as seen by the pilot. The actual entry point of the aircraft into the cloud can be seen by referring to Fig. 1 of Part II, where a × on the cloud photographs indicates the point of aircraft entry into the cloud.

Figure 2 shows the corresponding vertical section along the flight path of the T-28 for Penetration 80-1, and also the approximate locations of Cells W4 and W5. The reflectivity pattern shows W5 to be a cell with echo developing aloft as part of an overhang region and weaker than W4, which is in a more mature stage of development.

### a. Ice-water budget considerations

Many of the interesting features revealed by the analysis of the foil data can be seen in Fig. 3, which

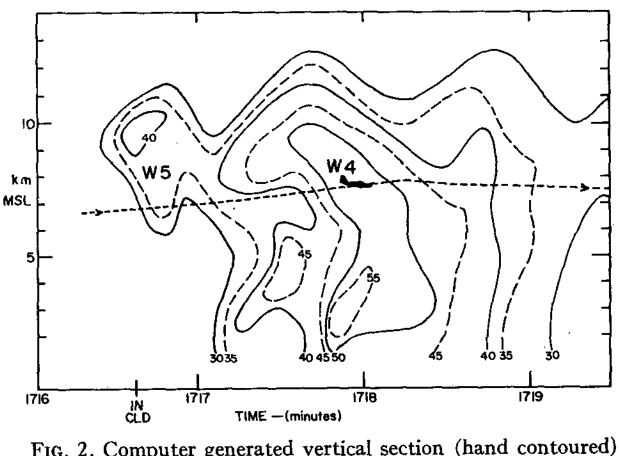


FIG. 2. Computer generated vertical section (hand contoured) along the track of Penetration 80-1. The dashed line shows the aircraft track and reflectivity factor contours are indicated in dBz. Cell W4 is in the mature stage while W5 has a recently developed echo aloft.

shows smoothed values of vertical velocity, $N_t$, $N_5$, PC, and PML as a function of time for Penetration 80-1. The smoothed vertical velocity curve masks the distinction between Cells W4 and W5, which is clearer in a more detailed presentation of data for the initial portion of Penetration 80-1 in Fig. 4.

Few actual in-cloud measurements of $N_5$ have been reported, but the values found in this study seem reasonable. The greatest concentrations of large particles ($N_5$) seemed to be at the edges of updraft regions (Fig. 3). Although the foil impactor was not carried on the aircraft during 1972 operational flights, these observations of $N_5$ are in qualitative agreement with the pilot's observations of large particles during penetrations of a storm on 22 July 1972 (Musil *et al.*, 1973).

The close relationship between PC and $N_5$ that was mentioned previously is very apparent in Fig. 3. The largest value of PC, when $N_5=0$, was only about 0.3 g m$^{-3}$; when larger values of PC were encountered, many of the particles were larger than 5 mm in diameter and therefore presumably in the form of graupel or hail.

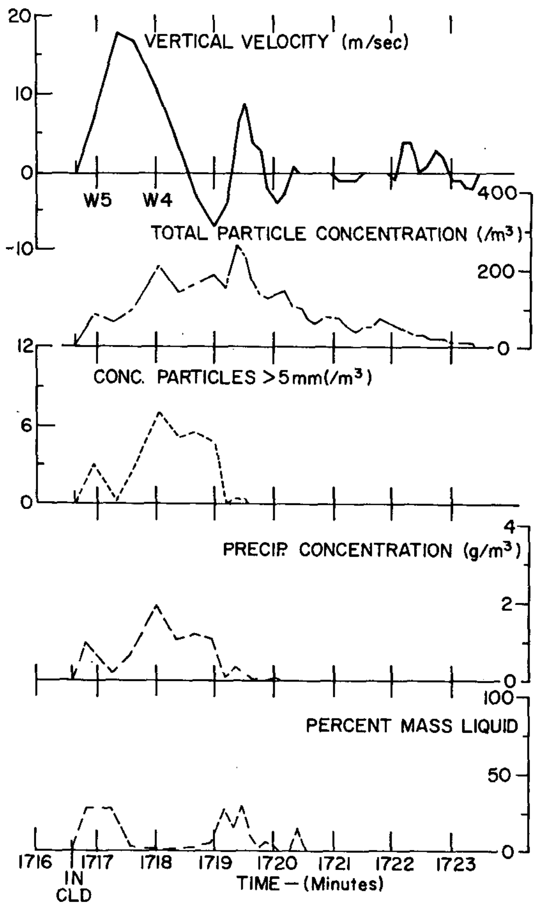


FIG. 3. Plots of smoothed vertical velocity, total concentration of particles, concentration of particles larger than 5 mm, precipitation concentration, and percent mass liquid for Penetration 80-1. Penetration was made at an average altitude of 7.2 km, which corresponds to a temperature of about −12°C. The distinction between Cells W4 and W5 is apparent in the more detailed vertical velocity curve in Fig. 4.

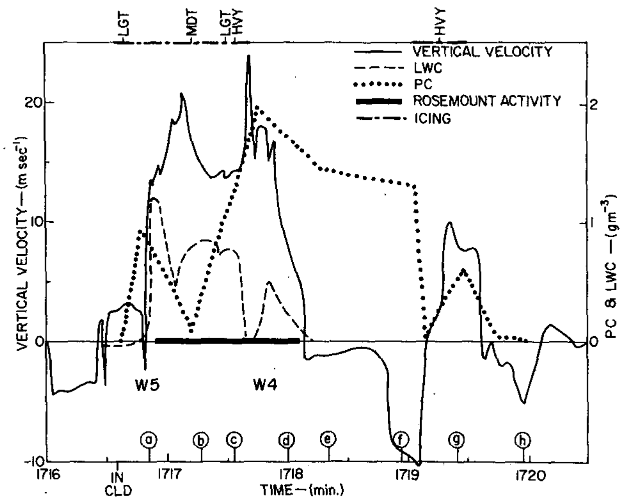


FIG. 4. Vertical velocity, cloud liquid water concentration (LWC), precipitation concentration (PC), Rosemount icing rate activity, and aircraft icing observations by the pilot for about the first half of Penetration 80-1. The vertical velocities are unsmoothed and therefore differ from those shown in Fig. 3. The letters along the time axis indicate the respective regions where the particle size distributions shown in Fig. 5 were determined.

Multiple updraft regions were encountered during this penetration and the highest values of PC straddled the interface between the updraft and downdraft region of Cell W4. Multiple updrafts were previously reported by Musil *et al.* (1973). Downdrafts encountered were generally weak with some penetrations having virtually no downdrafts.

Analysis of the foil data revealed that most of the precipitation size particles encountered in all of the penetrations were composed of ice or some combination of ice and water. It was impossible to determine the proportions of ice and water in the combination particles so, as noted in Section 2, they were taken to be ice particles for purposes of analysis. The proportion of the precipitation mass that was entirely liquid is shown for this penetration in Fig. 3. In general, the updrafts in the developing cells had significant amounts of liquid and the percent of the mass that was liquid depended to a certain degree upon the temperature at which the penetration was made; i.e., more ice was found at colder temperatures. Very little liquid precipitation was found in the regions where we observed significant numbers of large particles ($N_5$), which should fall in our "ice" category because liquid drops of such size are unstable.

Terminal velocities (McDonald, 1960) calculated for the particles observed in any of the penetrations on 9 July showed that most of the mass encountered was falling relative to the ground. Thus, in regions of high ice concentrations most of the particles came from regions higher and colder than the penetration level, where the mass would most likely be in the form of ice.

The presence of liquid in the updraft is shown in greater detail for a portion of Penetration 80-1 in Fig. 4. The vertical velocities shown are those actually measured by the T-28 during the penetration and are therefore somewhat different from the smoothed values shown in Fig. 3.

The double structure of the updraft is associated with the two cells (W4 and W5) shown in Figs. 1 and 2. The strong updraft indicated just after cloud entry is associated with W5, while the second updraft maximum is part of W4. The large horizontal extent of the updraft measurements shows the updrafts of the two cells to be joined, at least at T-28 flight level.

It can be seen in Fig. 4 that the updrafts associated with Cells W4 and W5 are characterized by relatively high cloud liquid-water concentrations, as indicated by a Johnson-Williams sensor; however, it is obvious that the highest values are in the younger cell (W5). This suggests that the large ice particles in W4 are in the process of depleting the available cloud water. This is especially evident in the downdraft region of W4, where nearly all evidence of liquid particles disappears. The large ice particles found on the edge of the updraft associated with W4 are in agreement with past T-28 observations (Musil *et al.*, 1973).

The Johnson-Williams device senses liquid particles smaller than 50 $\mu$m, which is well below the threshold to which the foil impactor responds. Furthermore, there is evidence of the presence of water in liquid form from the pilot's comments about aircraft structural icing and indications from a Rosemount icing rate probe. This combination of observations almost always indicated the presence of substantial, but unknown, numbers of liquid particles in the updrafts often at rather cold temperatures (e.g., near $-12$°C in this case). These observations are somewhat qualitative, but do provide strong supporting evidence of the presence of liquid precipitation particles in the updraft.

About one-third of the PC in the updraft for W5 was in the form of liquid precipitation-size particles (see PML values in Fig. 3) and part of the liquid was in the form of cloud droplets as indicated by the Johnson-Williams readings. An unknown amount of liquid may have been present in the intermediate size range between about 50 and 250 $\mu$. We know only in a very rough sense how liquid particles in different size regions contribute to aircraft icing or the behavior of the Rosemount icing rate device, which cannot give accurate quantitative values in regions of high liquid water concentration (Musil and Sand, 1974). Thus, we cannot interrelate all of the observations shown in Figs. 3 and 4 in complete detail, but the available evidence shows that the updraft regions associated with the developing cell (W5) had substantially greater quantities of liquid than the updraft associated with the mature cell (W4). This suggests that the coalescence process is important in the formation and growth of precipitation in this storm.

The presence of ice is probably a function of updraft strength and cloud temperature. Since the clouds in this study were part of a multicell system, we should expect to find substantial amounts of ice in all regions of the cloud except the areas of new development indicated by the strong, fresh updrafts (i.e., W5). According to current theories of hail suppression, seeding should take place in newly developing cells where large quantities of supercooled water are found.

### *b. Particle size distributions*

Particle size distributions (Fig. 5) were prepared from foil impactor observations for points indicated in Fig. 4 during Penetration 80-1. The small graph at the top of each distribution shows the percentage of the precipitation particles in each size interval that was determined to be in liquid form. The approximate sampling volumes for these particle size distributions ranged between 2 and 8 m$^3$.

Figure 5a shows a size distribution near the point of entry into the cloud (Cell W5) where roughly half of the particles (but only a third of the mass) were identified as liquid. The presence of the rather large liquid particles at the beginning of the penetration is probably due to coalescence growth simply because there appears to be no mechanism for transfer of particles between cells in this multicell storm (discussed further in Part V). Furthermore, hailstone growth models (Dennis and Musil, 1973), which allow coalescence growth of liquid particles as part of the hailstone growth mechanism, show similar sizes developing in approximately 10 min, the same amount of time that was observed in the Raymer storm for cloud turrets to grow and produce first echoes (Part I).

As the aircraft passed through the main updraft region into Cell W4 and encountered higher precipitation concentrations, the fraction of liquid particles decreased (Figs. 5b–d). In fact, with the exception of the large liquid particles found in the updraft region of the developing Cell W5 (Figs. 5a, 5b), the large particles encountered were predominantly ice. The number of rather large liquid particles found at this cold temperature ($-12$°C) contrasts with the observations of Knight *et al.* (1974), but the findings agree with the pilot who observed particles impacting and sticking to the windshield leading him to judge them to be liquid. High concentrations of particles larger than 5 mm occurred in regions of high PC (with the exception of Fig. 5g).

The observed size distributions are approximately exponential[6] in the small diameter region, but the

[6] Exponential functions plot as straight lines on the semi-logarithmic scales used in Fig. 5.

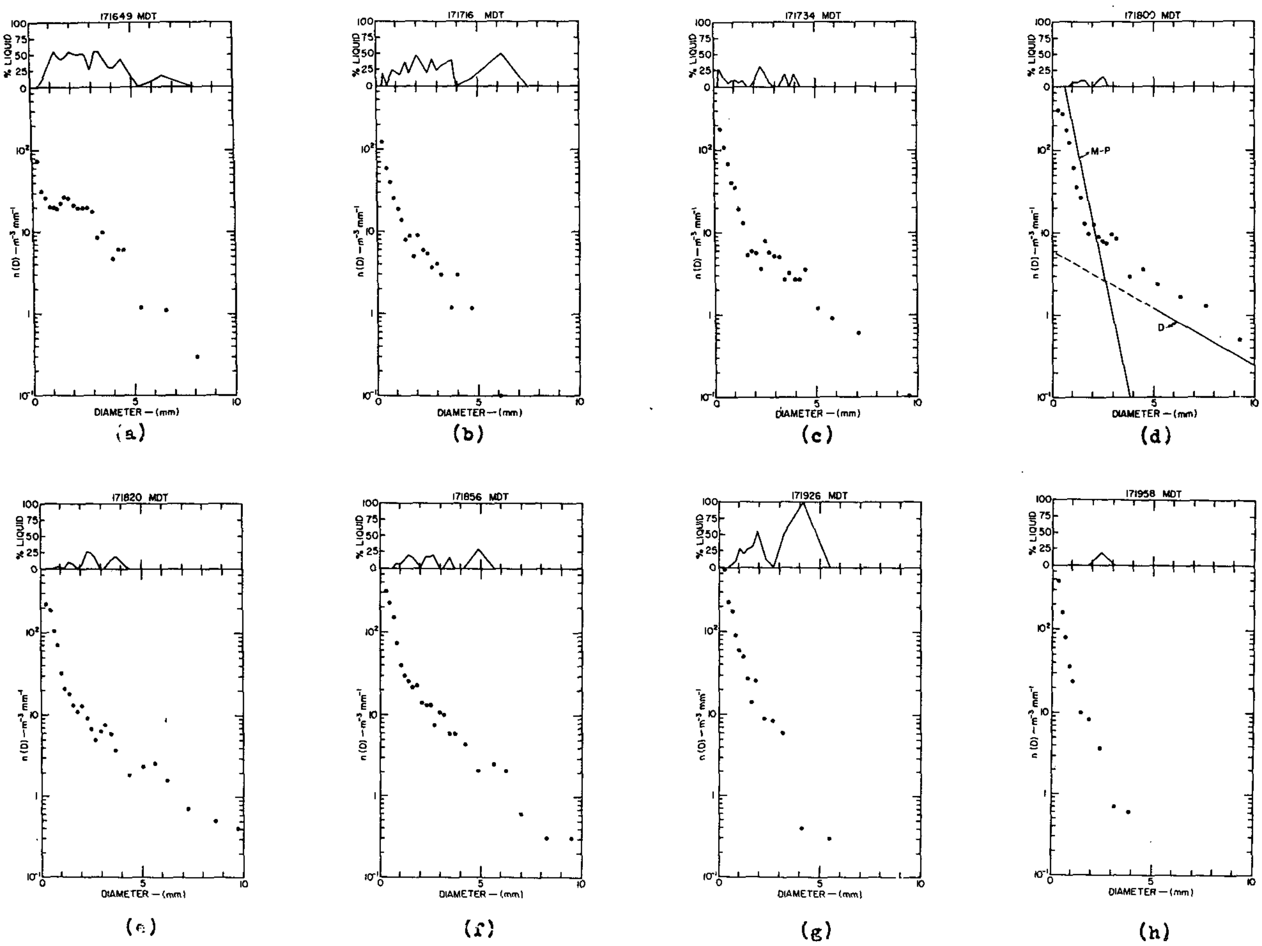


FIG. 5. Particle size distributions in the regions shown in Fig. 4. Appropriate times are indicated on each diagram. The upper portion of each diagram indicates the percentage of the particles in each size category that were identified as all liquid. Distributions represent the following conditions:

a—Edge of updraft of developing cell (W5).
b—Interior of updraft of developing cell, high PC.
c—Intermediate updraft region, high PC.
d—Edge of updraft of mature cell (W4), high PC.
e—Weak downdraft (2 m $s^{-1}$) of mature cell (W4).
f—Strong downdraft (8 m $s^{-1}$) of mature cell.
g—Interior of secondary updraft.
h—Secondary downdraft.

Lines in Fig. 5d show Marshall-Palmer (M-P) and Douglas (D) size distribution functions corresponding to the precipitation concentrations for particles smaller and larger than 5 mm, respectively.

Marshall-Palmer intercept value of $8\times10^3$ $m^{-3}$ $mm^{-1}$ (indicated in Fig. 5d) is well above the intercept for any reasonable best-fit line to the actual data. Thus, the present size distributions indicate fewer, but larger, particles than the Marshall-Palmer function for the same rainwater concentrations. One of these functions is shown in Fig. 5d for comparison; the M-P line shows the Marshall-Palmer raindrop size distribution function calculated for a precipitation concentration equal to that observed for all particles up to 5 mm. In addition to the disagreement in the intercept value, the fit also becomes poor for particles larger than 2 to 3 mm.

The distributions of the large particles (when present) can also be represented fairly well by exponential functions. However, the slopes differ from those of the lines appropriate for the smaller particles. Figure 5d also shows a Douglas (1964) hailstone size distribution function computed for the precipitation concentration in all particles larger than 5 mm in diameter; Federer and Waldvogel (1975) used a similar approach to fit their simultaneous observations of size distributions for both rain and hail. The slope of the Douglas line seems reasonable, but the intercept is obviously too low. Examination of Fig. 5, a–f, suggests that better agreement might be obtained by taking the dividing point between the "small" and "large" particle regions somewhere in the range 2–3 mm instead of at 5 mm. That might provide a reasonably good bi-exponential fit to the observations throughout the size spectrum.

In general, the observed particle size distributions can be approximated by one or two exponential functions. The intercept parameters for the small particle lines were always considerably smaller than the Marshall-Palmer values, while the large particle lines were in general conformity with the Douglas distribution. Further analysis of these size distributions now in progress will provide a more complete comparison with previously developed size distribution functions.

## 5. Summary and conclusions

The observed precipitation particle concentrations were generally similar to those reported by other investigators of cumulus clouds, but smaller than those commonly observed in rainfall at the ground. The characteristics of the particle distributions show a great deal of variation, and our data cover a short period of the storm's life history, making it difficult to infer a detailed ice-water budget. Most of the particles in the analysis were identified as ice particles, or particles containing both ice and water.

At first glance, such a predominance of ice might have strong implications for cloud seeding for hail suppression because most of the precipitation encountered during the penetrations was falling relative to the ground and was composed of ice or ice-liquid combinations. On the other hand, the updraft regions, especially those associated with newly developing cells, had substantial percentages of liquid particles which were often rising relative to the ground. Because of the presence of supercooled particles, these portions of the storms appear to be seedable, especially when one considers that substantial amounts of liquid were found at temperatures as cold as $-12°C$. The large amounts of ice found in part of this particular storm, which was unseeded, are a function of stage of development of the particular cell penetrated.

The particle size distributions were roughly exponential (or bi-exponential when large particles were present), but they showed fewer small particles and more large ones than the Marshall-Palmer raindrop size distributions would indicate. Sampling volume corrections need to be developed for the larger particles, but errors due to sampling volume considerations are unlikely to exceed a factor of two even in extreme cases.

The analysis of foil impactor data is extremely tedious and time consuming but it appears to provide useful information on precipitation size particles within hailstorms. The observations reported here should help to increase the understanding of precipitation processes in hailstorms and should aid in the development of numerical hailstorm models. Development should continue on devices that can automatically count and size particles over the entire size range as well as provide a capability to distinguish liquid from solid particles, thereby providing more information on the ice-water budgets of storms.

## REFERENCES

Bethwaite, F. D., E. J. Smith, J. A. Warburton and K. J. Heffernan, 1966: Effects of seeding isolated cumulus clouds with silver iodide. *J. Appl. Meteor.*, **5**, 513–520.

Brown, E. N., 1958: A technique for measuring precipitation particles from aircraft. *J. Meteor.*, **15**, 462–466.

Cataneo, R., and G. E. Stout, 1968: Raindrop size distributions in humid continental climates, and associated rainfall rate-radar reflectivity relationships. *J. Appl. Meteor.*, **7**, 901–907.

Cornford, S. G., 1966: A note on some measurement from aircraft of precipitation within frontal clouds. *Quart. J. Roy. Meteor. Soc.*, **92**, 105–513.

Dennis, A. S., and D. J. Musil, 1973: Calculations of hailstone growth and trajectories in a simple cloud model. *J. Atmos. Sci.*, **30**, 278–288.

Douglas, R. H., 1964: Hail size distribution. *Preprints 1974 World Conf. Radio Meteor. and 11th Wea. Radar Conf.*, Boulder, Colo., Amer. Meteor. Soc., 147–149.

Federer, B., and A. Waldvogel, 1975: Hail and raindrop size distributions from a Swiss multicell storm. *J. Appl. Meteor.*, **15**, 91–97.

Joss, J. and A. Waldvogel, 1969: Raindrop size distribution and sampling size errors. *J. Atmos. Sci.*, **26**, 566–569.

Knight, C. A., N. C. Knight, J. E. Dye and V. Toutenhoofd, 1974: The mechanism of precipitation formation in northeastern Colorado cumulus. I. Observations of the precipitation itself. *J. Atmos. Sci.*, **31**, 2142–2147.

May, E. L., 1974: Analysis of foil impactor data from armored aircraft penetrations of hailstorms. Report 74-9, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, 59 pp.

McDonald, J. E., 1960: An aid to the computation of terminal fall velocities of spheres. *J. Meteor.*, **17**, 463–465.

Miller, A. H., P. B. MacCready, Jr., and D. M. Takeuchi, 1967: Cloud physics observations in South Dakota cumulus clouds. Prepared for the Institute of Atmospheric Sciences by Meteorology Research, Inc., Altadena, Calif. 59 pp.

Musil, D. J., and W. R. Sand, 1974: Use of the Rosemount icing rate probe in thunderstorm penetrations. *Atmospheric Technology*, National Center for Atmospheric Research, Winter 1974–75, 140–142.

——, —— and R. A. Schleusener, 1973: Analysis of data from T-28 aircraft penetrations of a Colorado hailstorm. *J. Appl. Meteor.*, **12**, 1364–1370.

Sand, W. R., and R. A. Schleusener, 1974: Development of an armored T-28 aircraft for probing hailstorms. *Bull. Amer. Meteor. Soc.*, **55**, 1115–1122.

Schecter, R. M., and R. G. Russ, 1970: The relationship between imprint size and drop diameter from an airborne drop sampler. *J. Appl. Meteor.*, **9**, 123–126.

Schroeder, M. J., 1973: Cloud droplet and raindrop observations in cumulus clouds. Report 73-15, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, 38 pp.

Waldvogel, A., 1974: The $N_0$ jump of raindrop spectra. *J. Atmos. Sci.*, **31**, 1067–1078.